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COROTATION LAG OF SATURN'S MAGNETOSPHERE:
GLOBAL IONOSPHERIC CONDUCTIVITIES RE-VISITED

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ABSTRACT

Eviatar and Richardson (1986) calculated the Pedersen conductance of Saturn's ionosphere and obtained values far smaller than previous estimates. They concluded that the low Pedersen conductance explained the corotation lag in the magnetosphere. We have re-calculated the Pedersen conductance and confirmed the original estimates. The magnetosphere should corotate with the ionosphere. We suggest that the eddy diffusion coefficient in Saturn's upper atmosphere may be small enough to allow the ionosphere to be significantly de-spun relative to the interior.

INTRODUCTION

Eviatar and Richardson (1986) and Richardson (1986) have presented data from the Voyager 1 and 2 plasma science (PLS) experiments showing sub-corotation in the magnetosphere of Saturn. They attributed this corotation lag to a very low ionospheric Pedersen conductance, and concluded that the Pedersen conductance inferred from the corotation lag is consistent with that calculated from the neutral atmosphere model of Smith et al. (1983) and Voyager Radio Science data on the electron density profile (Tyler et al. 1981). However, their inferred ionospheric conductance for Saturn is four to six orders of magnitude smaller than previous estimates (e.g. Atreya et al. 1984).

We have re-calculated the Pedersen conductance of Saturn's ionosphere using the same neutral atmosphere model as was used by Eviatar and Richardson (1986). We confirm the earlier estimates that the ionospheric Pedersen conductance ranges from 0.3 to 17 mho near the terminator as a function of latitude. The source of the discrepancy appears to be that Eviatar and Richardson incorrectly included the ion density in the ion-neutral collision frequency term (their equations 9-11). Saturn's ionospheric Pedersen conductance is high enough to impose nearly perfect corotation between the ionosphere and the magnetosphere, contrary to the conclusion of Eviatar and Richardson (1986). There are, however, appreciable local time variations and possible localized latitudinal variations in ionospheric density as the result of water influx from the rings [Connerney and Waite 1984]. These ionospheric density changes from increased H^+ loss processes, as well as high-latitude enhancements in ionospheric density that may be expected from auroral

processes, will create spatial variations in conductance which may affect magnetospheric transport processes. Nevertheless, nearly perfect corotation is expected in the regions accessed by Voyager. This result must now be reconciled with the Voyager PLS observations of sub-corotation. We consider whether the ionosphere of Saturn can be de-spun relative to its conducting interior and suggest that the frictional torque exerted by the neutral atmosphere may be inadequate to enforce corotation of the ionosphere.

COROTATION LAG AND IONOSPHERIC CONDUCTANCE

Hill (1979) presented a model for the corotation lag in Jupiter's magnetosphere, in which a spin-up torque is exerted by a current system closing in the ionosphere so as to maintain partial corotation in the magnetosphere despite mass loading and plasma outflow. The torque exerted by one element of the polar cap ionosphere between colatitudes θ and $\theta + \Delta\theta$ is (in Gaussian units)

$$\text{Torque} = \sum_p 2\pi R^4 \sin^3 \theta \delta\Omega \frac{B_r^2}{c} \Delta\theta \quad (1)$$

where \sum_p is the height-integrated Pedersen conductivity, R the planetary radius, $\delta\Omega = \Omega_p - \Omega$ is the corotation lag (the difference between planetary and magnetospheric angular velocities), and B_r is the radial magnetic field component in the ionospheric polar cap. For a dipole field, we write $L \sin^2 \theta = 1$ with $\Delta\theta \simeq \Delta L / 2L^{3/2}$ and $B_r \simeq 2B_0$, where B_0 is the surface equatorial field. We define $\dot{M}(L)$ as the rate of mass addition in grams s^{-1} within L , so that in

a steady state $\dot{M}(L)$ is also the rate at which mass flows outward through L . Then the rate of angular momentum addition within $(L, L + \Delta L)$ is $\Delta L d/dL(\dot{M} L^2 R^2 (\Omega_p - \delta\Omega))$ and is balanced by the torque exerted from the two polar cap ionospheric elements (Hill, 1979):

$$\frac{d}{dL} \left[L^2 \dot{M} (\Omega_p - \delta\Omega) \right] = \frac{\sum_p \frac{8\pi R^2 \delta\Omega B_o^2}{L_c^3}}{2} \quad (2)$$

If there is outflow but no local mass loading, so $\dot{M} = \dot{M}_o$ is constant, then

$$0 = L^5 \frac{d}{dL} (\delta\Omega) + \left(4L_o^4 + 2L^4 \right) \delta\Omega - 2L^4 \Omega_p \quad (3a)$$

$$L_o = \left(\frac{2 \sum_p \pi R^2 B_o^2}{\dot{M}_o c^2} \right)^{1/4} \quad (3b)$$

Equation (3a) gives the qualitative behavior of the corotation lag $\delta\Omega$ in Jupiter's magnetosphere (Hill, 1979), and L_o is the characteristic distance at which corotation breaks down ($L_o \approx 23$ for Jupiter). If L_o is evaluated for Saturn, we find

$$L_o \text{ (Saturn)} = 56.4 \left(\frac{\sum_p}{1 \text{ mho}} \frac{10^3 \text{ g s}^{-1}}{\dot{M}_o} \right)^{1/4} \quad (4)$$

For expected values of $\dot{M} \approx 10^3 \text{ g s}^{-1}$ at Saturn (Cheng et al. 1986, Eviatar and Richardson, 1986) and expected values of $\sum_p \sim 1 \text{ mho}$ (see below), we find $L_o \approx 56$ which is far outside the dayside magnetopause at 18-24 R_s . This result

indicates that an ionospheric Pedersen conductance of only 10^{-2} mho would already suffice to enforce essentially perfect corotation out to $L \gtrsim 20$. This result is supported by Eviatar and Richardson (1986), who show that $L_0 \approx 9$ would be required to match the observed Saturnian corotation lag; according to (4) this would require $\Sigma_p < 6 \times 10^{-4}$ mho for $\dot{M} \approx 10^3 \text{ g s}^{-1}$.

However, (3) and (4) neglect local mass loading. This is a good approximation for Jupiter, where most of the corotation lag is found outside the Io torus and \dot{M} is nearly independent of L in the region of interest. However, at Saturn \dot{M} increases steadily out to the magnetopause, where it reaches a value $\dot{M}_0 \approx 10^3 \text{ g s}^{-1}$. To estimate the effect of local mass loading, we can re-write (2) after some algebra in the equivalent form

$$\Omega = \frac{\Omega_p}{1 + \frac{\alpha L^4 \dot{M}}{4 L_0^4 \dot{M}_0}} \quad (5a)$$

$$\alpha = \frac{d \ln (\dot{M} \Omega L^2)}{d \ln L} \quad (5b)$$

The mass loading is smoothly distributed over a broad range in L , since it arises from ionization of neutral clouds maintained by sputtering from icy moons and escape from the atmospheres of Titan and Saturn (e.g., Cheng et al. 1986). Hence α must be of the order of unity (recalling that Ω decreases with L). However, when $\dot{M}_0 = 10^3 \text{ g s}^{-1}$, then $L_0 \approx 56$ and $L^4 \ll 4 L_0^4$. Since $\dot{M} < \dot{M}_0$, the differential equation requires Ω to be nearly equal to Ω_p regardless of the detailed form of $\dot{M}(L)$.

We conclude that for small L compared to L_0 , the corotation lag is generally small, more or less independent of how the mass loading is spatially distributed. If $\Sigma_p \sim 1$ mho and $\dot{M} \sim 10^3 \text{ g s}^{-1}$ at Saturn, then corotation should be well enforced throughout the core magnetosphere.

Pedersen Conductance

We have completed new calculations of the Saturn ionospheric conductivity. The results are shown in Table 1. The values are obtained using the Smith et al. (1983) atmosphere and digitized ionospheric densities from the ionospheric profiles of Lindal et al. (1985). These ionospheric densities are measured at various latitudes near the terminator as indicated in the table. Therefore to estimate changes in conductance due to local time variations, we have multiplied the Lindal et al. terminator profile by 16 or 0.06 to represent noon and midnight, respectively. The factor was taken from the variation in the peak electron density inferred by Kaiser et al. (1984) from SED cutoff frequencies. The limitation of this approach is that we do not expect all altitudes to change by the same factor, but if the peak factor is correct then the gross variations in conductance as a function of local time should be properly represented by such an approach. The assumed ionospheric composition is a mixture of H^+ , H_3^+ , and heavy water ions as inferred from model calculations. However, other choices in composition did not significantly affect the results. In fact, the results did not change by over a factor of two to three when a different atmospheric model [Festou and Atreya, 1982] was used or when the existence of low lying ionospheric layers was ignored.

Even in the most extreme case shown in Table 1 (midnight, latitude 1 degree south) the integrated Pedersen conductivity of 1.8×10^{-2} mho was almost two orders of magnitude higher than those reported by Eviatar and Richardson [1986]. Indeed the lowest value calculated on the dayside exceeds 0.3 mhos and general daytime values are on the order of 1 to 10 mhos whereas night values generally vary from 0.1 to 1 mho. There are localized mid-latitude bands near -37° and $+42^\circ$ where ionospheric densities decreased to 1 to 2% of the equatorial electron density at the same local time [Kaiser et al., 1984]. These latitudes are connected magnetically to the inner edge of Saturn's B ring where Northrop and Connerney (1987) have theoretically calculated an increased ring erosion generated influx of water to the atmosphere that could significantly increase ionospheric loss processes and reduce ionospheric densities in this region. Here the values of the conductivity might conceivably fall to 10^{-4} mho on the nightside but should remain above 10^{-2} mho on the dayside. Such localized latitudinal decreases might also be possible at higher latitudes due to the influx of charged water ions from satellite erosion processes, but the decrease in conductance should be negligible since the expected water ion influx should be significantly less than from the rings. In no case do we expect the dayside Pedersen conductance to fall below 10^{-2} mho. In fact at higher latitudes near the auroral zone ($78^\circ - 81^\circ$) we expect the Pedersen conductance to exceed 10 mhos with a weakened local time variation. The conductance may peak at values ~ 50 mho between latitudes 78° and 81° and then decrease to $\sim 10^{-2}$ mho at the poles. With the high conductance near the auroral zones and the low conductance in the mid-latitude bands mapping to Saturn's B ring, the ionospheric Pedersen conductance is highly variable, affecting transport processes in the magnetosphere.

We emphasize that very low Σ_p values less than 10^{-2} mho are expected only at latitudes that map to Saturn's main ring system ($L \lesssim 2$). The corotation lag reported by Eviatar and Richardson (1986) applies only to $5 \lesssim L \lesssim 15$, for which the calculated Σ_p is in all cases $> 10^{-2}$ mho. As was noted above, such a high Σ_p value should enforce corotation throughout the observed region. A small Σ_p near $L = 2$ would be of no consequence for corotation lags at $L > 5$. We conclude that Saturn's ionospheric Pedersen conductance is more than adequately high to enforce corotation of the magnetosphere with the ionosphere.

DISCUSSION AND CONCLUSIONS

The observations of sub-corotation in the magnetosphere (Richardson, 1986) must now be reconciled with the high Pedersen conductance of Saturn's ionosphere. One possibility for resolving this apparent conflict is that Saturn's ionosphere may be de-spun relative to the conducting interior of the planet. Eviatar and Richardson (1986) previously considered the atmospheric torque from upward transport of angular momentum and concluded that it was adequate to maintain corotation of the ionosphere. We now re-examine the atmospheric torque and conclude that the magnetosphere can indeed de-spin the ionosphere.

The upward angular momentum flux between colatitudes θ_1 and θ_2 which gives the atmospheric torque on the ionosphere is

$$T_{\text{atm}} = 2\pi R^4 D \frac{d(\rho\Omega)}{dz} \left(\frac{\cos^3 \theta}{3} - \cos \theta \right) \Big|_{\theta_1}^{\theta_2} \quad (6)$$

correcting a minor error in eq. (5) of Eviatar and Richardson (1986). Here ρ is the neutral density and D is the eddy diffusion coefficient. Eviatar and Richardson adopt $D = 1.1 \times 10^8 \text{ cm}^2 \text{ s}^{-1}$ and approximate $d(\rho\Omega)/dz$ by the value $\rho_{1100}\Omega_p/1400 \text{ km}$, where ρ_{1100} is the density at 1100 km altitude and Ω_p is Saturn's rotation angular velocity, as above. They then estimate that T_{atm} between $L = 8$ and $L = 25$ exceeds the mass loading torque by about a factor of six.

This procedure, however, may overestimate the atmospheric torque. The Smith et al. (1983) neutral atmosphere model, used by Eviatar and Richardson and by us to calculate Σ_p , actually assumed $D = 5 \times 10^6 \text{ cm}^2 \text{ s}^{-1}$. For consistency, this smaller value of D should probably be used to estimate T_{atm} , with the result that T_{atm} would be reduced by a factor of 20 and would no longer exceed the required mass loading torque. Smith et al. (1983) investigated several atmosphere models with various values of D , and they concluded that models with D as large as $10^8 \text{ cm}^2 \text{ s}^{-1}$ were "definitely inconsistent" with the UV data.

Given the large uncertainty in D , it is not clear whether the frictional torque T_{atm} does or does not exceed the mass loading torque. However, it seems safe to conclude that the two torques are comparable, so the ionosphere can be significantly de-spun relative to the interior. Indeed the observed sub-corotation in the magnetosphere and the high calculated Σ_p provide a strong argument in favor of a low enough D to permit significant slippage of the ionosphere relative to the interior.

Finally, another possibly important effect has not yet been considered, namely, that thermospheric wind systems may induce significant magnetospheric convection and may cause large deviations from corotation, both in flow velocity and magnitude. Further work is needed to investigate this issue.

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Table 1

Height-Integrated Pedersen Conductivities (mhos)

<u>Local Time</u>	<u>Latitude</u>			
	<u>1°S</u>	<u>31°S</u>	<u>73°S</u>	<u>36°N</u>
terminator	0.31	0.43	17	14
noon	4.9	6.8	260	220
midnight	0.018	0.25	0.96	0.79

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